Jon

Look like people waiting for big industry to do
but the scholars think they know the way, but not tried!

AUTOMOTIVE GAS TURBINES:
GOVERNMENT FUNDING AND THE WAY AHEAD

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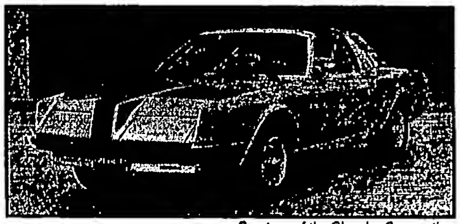
INTRODUCTION

The first article in this series (GGTN May/June 1995) took as its theme the role of the innovator-entrepreneur, focusing on George Huebner at Chrysler and Maurice Wilks and Noel Penny at Rover. In the second (GGTN August/September 1995) we looked at one innovator, Sven-Olof Kronogard in Sweden, and one team, at Ford. I recognized that my choices of role-models could lead me to be accused of bias. The potential for such an accusation is bound to be strengthened in this third and last article. The engines and developments that we discuss here are all carried out by teams, and they have all been supported predominately by government funding. I believe that in some cases the designs show flaws that I will have the temerity to name. I will further risk condemnation by stating what directions I think the industry should be following in the future.

The last article covered the period up to the first "energy crisis." The earlier developments in automotive gas turbines had been pursued because their proponents felt them to be just better engines than the existing spark-ignition and compression-ignition engines. The rapid increase in oil prices and the threat of very sharp reductions in supply propelled the turbine engine into a potentially starring role. I was on panels of no fewer than three national committees or commissions inquiring into alternative automobile engines, started partly by claims being made by steam-engine enthusiasts that modern versions of this ancient engine would be both cleaner and more efficient. The commissions all found, however, that the two alternative engines with the highest potential to reduce both fuel consumption and pollutant emissions were the Stirling engine and the gas turbine. The U.S. Environmental Protection Agency was created during this period to concentrate the nation's attention on the need for change. It issued rules, not yet met by any viable engine except the gas turbine, requiring a reduction in carbon-monoxide emissions to around 1% of then-existing levels, and similar reductions in other pollutants. Congress seemed to feel that the free market would not bring about change rapidly enough, and funded several programs aimed at producing better alternative engines, including several gas turbine projects. Congress also mandated reductions reaching about 50% in the "fleet-average" fuel consumption of automobiles. (The free market did, in fact, respond rather well, with greatly improved spark-ignition engines meeting most of the targets. This engine is still getting better, at the cost of increasing complexity.)



Courtesy of the Chrysler Corporation.

Turbine concept car built for the U.S. Department of Energy by Chrysler Corporation in 1977.

This article, then, is principally about the automotive gas turbines that have come from government-funded programs in the United States. We will also discuss briefly the MITI-funded Japanese projects and the Daimler-Benz PWT 110 engine. The 1.1-MW U.S. Army tank engine will be included, although it is at the extreme high end of the automotive power range.

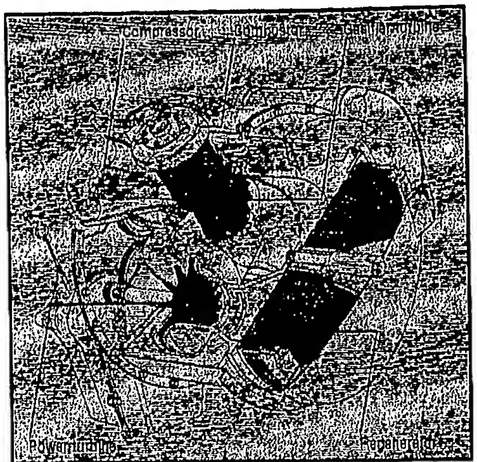
THE AGT PROGRAM

"AGT" stands for "advanced gas turbine." The initials were used for the army-tank engine, the AlliedSignal Engines' AGT1500, of which more later, and for the three automobile engines designed for a U.S. Department of Energy program administered by NASA-Lewis: one by Allison, then a division of General Motors (the AGT-100); one by Garrett-Ford, later Garrett (the AGT-101); and one (the AGT-102) by Chrysler and Williams International, which was funded for only one year[1].

The general aim of the overall NASA program was a substantial improvement in fuel economy and a reduction in emissions in an engine that could be mass-produced at costs comparable to those for the spark-ignition engine. In practice, this mandated ceramic engines. The general aim was to operate at a gas temperature entering the turbine of 2500F (1644K). Both the engines that reached the hardware stage, the AGT-100 and the AGT 101, used metal centrifugal compressors and ceramic radial-inflow turbines, combustors, regenerators and hot ducts. Beyond that design agreement there was substantial divergence in direction.

AGT-100

The Allison AGT-100 design (Figure 1) conformed to earlier norms in having a two-shaft system, with one



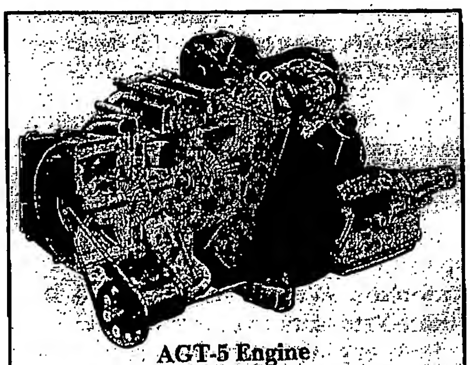
1981 NASA, DEN-3-168.

Figure 1. Allison AGT-100 all-radial two shaft engine.

turbine driving the compressor and the other connected to the torque converter and four-speed automatic transmission. It was highly unusual in having both turbines of the radial-inflow type[2]. It is not an attractive arrangement. The flow leaving the high-pressure turbine, in most conditions of operation having a considerable degree of swirl, passed through a 90-degree bend into the "snail-shell" inlet scroll of the power turbine. In my experience, losses even in short lengths of conical-annular ducting connecting axial-flow turbines can be very high. The losses in a swirling flow turning through about 270 degrees into the power-turbine rotor must have been very significant.

The tests of the ceramic high-pressure turbine rotor was plagued by blade tip failures. Many possible causes were examined including vibration input from stator wakes and thermal stresses. It was concluded that foreign-object damage (FOD) was the most likely cause, but no foreign object was identified. However, a single grain of sand becomes a sufficiently large foreign object when it is required to attain an inward acceleration approaching one million times gravitational acceleration to pass through a high-pressure ratio radial-inflow turbine. A small solid particle, lagging the nozzle airflow in speed, will then bounce off the rotor tips on to the nozzle vanes and back to the rotor tips until pieces break off to add to the speed of erosion.

The single rotary ceramic-honeycomb regenerator used for the AGT-100 engine was far from optimum with regard to the need to balance pressure drops. With nearly equal face areas for the hot and cold flows, the hot (low pressure) flow would have a penalizingly large pressure drop, while the cold flow at a pressure of about 4.5 bar would have a pressure drop too low to assure good flow distribution. We will see that this is a common design problem.



Courtesy of Allison Engine Company.

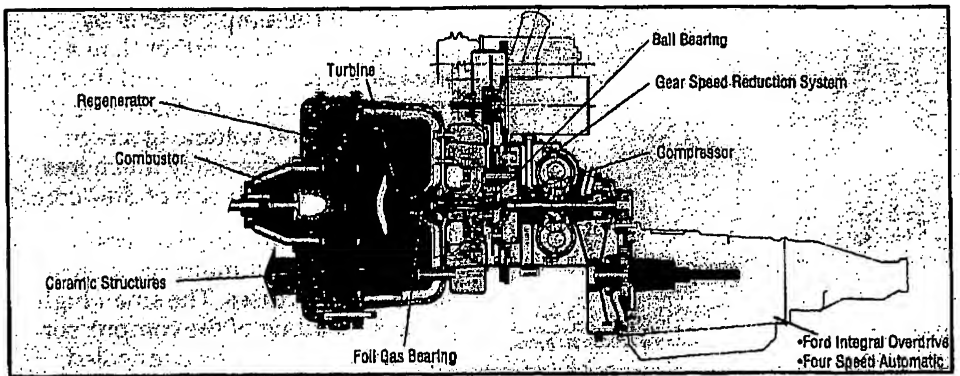
Figure 2. Allison AGT-5 radial-axial engine.

Success came late to this program when it inherited hardware from GM Research with a two-stage axial ceramic turbine - the AGT-5, Figure 2 - rather than the two-stage radial[3]. These rotors were subsequently modified to use lower-aspect-ratio blading to survive FOD. The AGT-5 ran to full speed and full temperature. "Monolithic Si_3N_4 rotors have successfully survived impacts caused by ingesting a variety of foreign objects: included are pieces of a failed superalloy metallic combustor dome, molten metal turbine vanes, combustor hard carbon, engine insulation chunks, and pieces of metallic screen wire"[3]. (Perceptive readers will discern that I am no fan of high-speed radial-inflow turbines. It gives me no pleasure to report that I tried at the start of the program to get the AGT managers to be aware of the risks in the directions they were taking, but to no avail.) Axial turbines are far more compact[4], have lower inertia, and can be "multistaged" with high efficiency. A proponent of the opposite view, Homer J. Wood, who has worked with and designed successful radial-inflow turbines since 1947, points out that some of the most reliable turbines are radial-inflow, but that they must be properly designed[5]. He regards brittle ceramic rotors as a "doubtful prospect" in either axial- or radial-flow.

The AGT-1 00 program (which was succeeded by the ATTAP - advanced turbine-technology applications project) demonstrated that quite large and complex shapes can be formed in ceramic and can maintain their integrity in the high-temperature high-stress conditions of operation of a gas turbine engine. It also dramatically demonstrated the virtues of axial-flow versus radial-flow turbines when high tip speeds are used for small-diameter ceramic rotors.

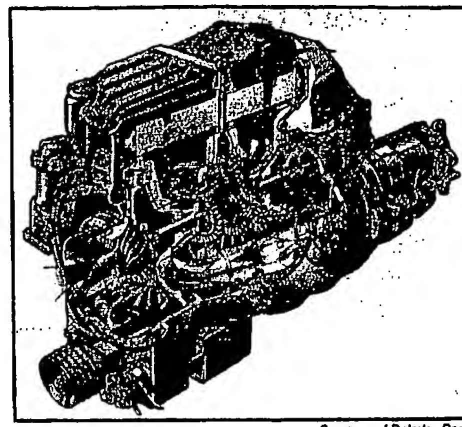
AGT-101

This Garrett-Ford engine differed radically from previous automobile engine designs in having a single shaft carrying a single-stage radial-outflow compressor and a single-stage radial-inflow turbine (Figure 3). (This design choice implies the use of a continuously-variable transmission or CVT. The Chrysler-Williams team chose similar specifications for the AGT-102 and showed a metal-belt CVT running in variable-width conical pulleys.) The power output selected for AGT-101 was considerably smaller than that of the AGT-100 - 75 versus 100 kW - and the pressure ratio was higher at 5:1. Consequently, the tip speed of the turbine rotor was higher and the diameter smaller, leading to even higher inward accelerations needed for solid particles to pass through the rotor. Accordingly, the program ran into severe erosion problems when the engine was run at full speed and temperature with a ceramic rotor[6]. Carbon formation from the combus-



Garrett Corporation, 1980.

Figure 3. The Garrett-Ford AGT-101 single-shaft all-radial engine.



Courtesy of Daimler-Benz.

Figure 4. Daimler-Benz PWT 110 radial-axial two-shaft engine.

Photo by Dave Lindsey.

Figure 5. Daimler-Benz PWT 110 demonstration automobile on display at ASME TURBO EXPO '90 in Brussels, Belgium.

tor was blamed. It was believed that a tip-speed reduction from 700 - 565 m/s (2300 - 1850 ft/s) was required to eliminate the problem. The turbine was modified to be of a mixed-flow configuration with blades that approximated axial impulse shapes. Thus the same enthalpy drop and power output could be obtained with the lower blade speed. However, one would expect a reduction in turbine efficiency from the considerably increased aerodynamic loading.

The (previously) projected engine thermal efficiency for the AGT-101 was very high: 45% at design point, increasing to over 46% at the half-power point, and maintaining 43% even at 20% power. The internal flow leakage past regenerator seals and through the turbine-end air-lubricated foil bearing was found in early tests to be far too high for these ambitious performance levels to be achieved. The AGT 101 is a compact unit, with a radial-outflow diffuser after the radial-inflow turbine, promising a high recovery of turbine-outlet kinetic energy. The regenerator, having apparently a precisely 50-50 flow split, will suffer from worse pressure-loss and flow-distribution problems than the AGT 100 engine (because of the higher pressure ratio).

CGT, JARI & MITI

"CGT" stands for the ceramic gas turbine which has been designed by the Japan Automobile Research Institute and funded by the Ministry of International Trade and Industry[7]. Like the AGT-101, it has a single shaft with a single-stage metallic centrifugal compressor having a pressure ratio of 5:1 and a single-stage ceramic radial-inflow turbine. Somewhat similar failure problems have occurred in the radial turbine. The CGT has a higher output: 100 kW (134 hp) versus 75 kW (100 hp) and it has two rotary regenerators rather than the single unit for the AGT-101. It lacks that engine's good radial diffuser after the turbine, having what seems to be a long, high-loss, slightly conical tube in which there is almost certain to be reversed flow at the center. It has the same 50-50 area split in the regenerator that will undoubtedly reduce its effectiveness. The program has been funded for seven years starting in 1990, and whatever our criticisms we are all well aware that Japanese development teams have a record of meeting their objectives.

THE DAIMLER-BENZ PWT 110 ENGINE

This engine, developed by Mercedes-Benz in Stuttgart, was partly funded by the German Federal Ministry for Research and Technology. The project started in 1978, led by E. Tiefenbacher[8], and has resulted in the most successful of the ceramic-engine projects to-date. Overall the PWT 110 engine conforms to what was called the baseline design in the first of these articles: it has a centrifugal compressor driven by an axial turbine with a second axial turbine on a second shaft driving the load (Figure 4). A single rotary ceramic honeycomb regenerator is mounted at the top of the engine and the single combustor is at the side. The pressure ratio is over 4: 1, and in the first phase of the program the turbine-inlet temperature was 1250 C (2280 F) and the engine output was 94 kW. In the second phase the temperature was to be increased to 1350 C (2460 F) and the power would then reach its design level of 110 kW. The turbine disks have been machined from a solid blank and have been produced by hot-pressing, slip casting and injection molding silicon nitride, all with general success. The engine has been installed in a car that has done considerable distances (Figure 5). It is believed to be the only operating automobile to have met the U.S. federal emissions 1975 standards.

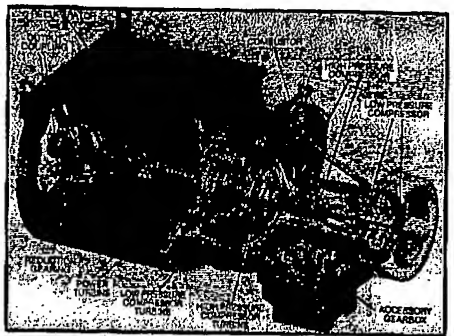
THE ARMY TANK ENGINES

By numbers produced alone, the AlliedSignal Engines' AGT1500 (the power plant for the M1 series of Abrams Main Battle Tanks – Figure 6) would have to be ranked as the most successful automotive-propulsion gas turbine, and the most successful heat-exchanger engine in any field. It was designed by a team headed by Dr. Anselm Franz in the 1960s[9]. Franz designed the renowned Junkers Jumo axial jet engine in Germany in WW II. His tank engine bears many signs of its creator. The axial compressors look, apart from the small size, very similar to that of the Jumo engine (we have one at MIT) in that it has almost 100-percent reaction.

Courtesy of General Dynamics Land Systems.

Figure 6. M1A2 Abrams Main Battle Tank.

The AGT1500 (Figure 7) is a three-spool engine. The low-pressure axial compressor is driven by the second-stage axial turbine, and the high-pressure axial-radial compressor by the high-pressure turbine. The low-pressure turbine drives the transmission via a long shaft that passes through the center of the stainless-steel recuperator. Figures given by AlliedSignal (formerly Textron Lycoming) to a congressional committee indicate that the low-pressure compressor is, considering its small size, highly efficient (about 0.88 polytropic) while the high-pressure compressor, including the radial component, has an efficiency of about 0.80, as one would expect with the small blade heights required. The overall pressure ratio is 14.0. The ingenious two-pass cross-flow heat



Courtesy of AlliedSignal Engines.

Figure 7. The AGT1500 Gas Turbine Engine.

exchanger has an effectiveness of only 0.68. When the engine was designed this was near a typical level of effectiveness. The space available does not allow a larger recuperator. At this time, thirty years after the design was chosen, it is easy to advocate the use of a much-higher effectiveness regenerator and a much-lower-pressure-ratio cycle. The replacement engine is not going in this direction. It is the direction, however, that I recommend for future engines.

FUTURE AUTOMOTIVE ENGINES

All my biases are about to be exposed. I have, in fact, paraded them previously[10]; and they led to my being asked to write these articles. I strongly believe in the potential of multi-stage engines with high-effectiveness regenerators (e.g. 0.975) and low design-point pressure ratios (e.g. 2.5:1), for the following reasons:

1. Regenerators can be far more compact than recuperators (fixed-surface tubular or plate-fin heat exchangers) because the volume of a heat exchanger is proportional to the square of the hydraulic diameter[11]. The optimum hydraulic diameter is 0.5 - 0.75 mm, easy to produce and operate in a flow-reversing regenerator and very expensive and susceptible to blockage in a recuperator of the same effectiveness.

2. Ceramic regenerators are currently extruded. Higher effectiveness can be attained at the simplest level by cutting off a thicker rather than a thinner slice. The casing and ducting remain of similar size. Therefore the increase in total volume of a regenerator is proportionately much less than the increase in size of the "core."

3. As regenerator effectiveness is increased, the optimum cycle pressure ratio decreases. The small high-pressure blading of the compressor and turbine is thereby eliminated, and with it a principal source of loss. Therefore, the polytropic efficiencies of compressors and turbines increase as the design-point pressure ratio is reduced. The thermal efficiency of the cycle increases accordingly.

4. The off-design efficiency of low-pressure-ratio compressors and turbines increases versus higher-pressure-ratio equivalents. The flow passages in these machines are sized to take the flow at design-point densities. At off-design, i.e. at lower densities, the mean axial flow has to accelerate greatly in compressors and decelerate in turbines relative to their design-point velocities, causing penalizing flow incidences. This acceleration and deceleration is less for low design-point pressure ratios and leads to higher efficiencies. Automotive engines must have high efficiencies at part load because that is where they operate almost all their lives.

5. Although lower pressure ratios enable single-stage compressors and turbines to be used at lower aerodynamic loading than for high-pressure ratio cycles, I advocate the use of two- or three-stage centrifugal compressors and axial turbines for three reasons.

(i) In a single-stage compressor or turbine, the kinetic energy in the outlet flow (even after an effective diffuser) can represent perhaps nine-to-twelve points in efficiency. In a similar three-stage machine, the outlet KE would be three-to-four points. The resulting increase in what is called the "total-to-static" efficiency

is important to automotive engines, because the KE is of no value to the succeeding components.

(ii) The multistage compressors will have lower relative Mach numbers at the inducer tips and at the inlet to the vaned diffusers, reducing other sources of considerable loss.

(iii) The blade speeds can be reduced to a point where the compressor rotors could be injection-molded in high-strength reinforced resin, and the (axial-flow) turbine stages could be molded using the technology and low-cost ceramic materials developed for the mass-production of automobile turbocharger rotors. (Nissan Motors introduced, at the Yokohama Expo, October 1995, injection-molded turbocharger compressor rotors as a complement to their ceramic turbine rotors.)

6. The use of low blade speeds virtually eliminates the risk of foreign-object damage.

7. Multistage axial-flow turbines conserve kinetic energy from one stage to the next.

8. The rotating inertia of axial turbines is far lower than of the equivalent radial turbines, and the inertia of three low-speed rotors is lower than that of one high-speed rotor.

9. The large seal-leakage losses and rapid seal and matrix wear of present rotary regenerators must be reduced. I am an interested party here, because MIT has patents on a system to reduce both leakage and wear considerably.

10. The low shaft speed saves at least one gear set for mechanical-drive engines over the requirements for single-stage high-pressure-ratio engines.

The resulting low-cost very-high-efficiency engine will be slightly larger than the present generation of high-pressure-ratio single-stage machines. The high efficiency results in the specification of a lower mass flow, compensating to some extent for the increase in volume resulting from increasing the effectiveness of the regenerator and from using multistage compressors and turbines. (The turbines and compressors in present 70-kW and 100-kW engines are very small, and an increase in turbomachinery size will not produce anything like a proportional increase in overall engine size).

WILL THE AUTOMOTIVE GAS TURBINE BE ADOPTED?

Although I firmly believe that automotive gas turbines could be produced less expensively than present engines and could produce power at considerably lower fuel usage with significantly lower emissions, I cannot look into a crystal ball and forecast the adoption of these engines. The massive investment in all the infrastructure built up to produce and maintain the spark ignition engine, coupled with the significant investment required to develop and produce the new engine, would require a revolution to bring about change. The free market in the U.S. does not seem enough to do so, given that the current automobile engine is so highly regulated. Perhaps the most likely place for a change to occur will be in Japan, where the pressures for greater fuel economy are highest.

CONCLUSIONS

In this final article the automotive gas-turbine developments surveyed have been principally those resulting from government-funded programs. It is not clear to me that they have advanced the turbine any closer to final adoption because of what I consider to have been some unwise design directions. I have immodestly given my own prescription for what I believe to be more promising future developments. However, I have not forecasted an early adoption of any type of automotive gas turbine anywhere in the world except possibly Japan, even though early versions demonstrated superiority over the spark-ignition engine.

ACKNOWLEDGMENTS

Many friends have helped me with these articles and have provided illustrations. George Huebner, Noel Penny, Art McLean and Peter Beardmore deserve special mention. David Lindsay has been not only a supportive editor but has put a great deal of successful effort into finding, and getting permissions to use several other valuable photographs. My students, past and present, have provided valuable analyses and back-up. To all I am extremely grateful. ✹

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Jon Enter Now the TMA-Power Co!

AUTOMOTIVE GAS TURBINES: THE PIONEERS

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INTRODUCTION

The automotive gas turbine was conceived of almost sixty years ago. Yet the long-lived and often-condemned spark-ignition (SI) and compression-ignition piston engines continue to overcome challenges and to become cleaner and more reliable. Is the automotive gas turbine then, just of historical interest?

Only a few years ago pundits felt that the use of gas turbines for central electric-power generation was a hopeless dream, just as earlier experts predicted that gas turbines could never be used for aircraft propulsion. These people were totally wrong. Critics of the automotive gas turbine may be just as wrong. In this first article of a series, we will look at the pioneers of this technology. In later articles, we will show that the dreams of George Huebner, Maurice Wilks and Noël Penny, among many others, may still be realized.

GEORGE J. HUEBNER, JR.

In 1938 George Huebner, age 28, was already assistant chief engineer of Plymouth, and a rising star at Chrysler Corporation. He had graduated from the University of Michigan six years earlier and wanted to make a radical improvement in automobiles. Having looked at the gas turbine, Huebner decided that it could be the successor to the long-lived piston engine and instituted a study to find out if his engineering intuition was accurate[1].

Few people had heard of the gas turbine in 1938, even though its thermodynamic cycle had been identified at the end of the eighteenth century. The first attempts at producing actual engines started at the turn of the twentieth century, and they resulted in a succession of expensive failures. However, one of these failures had been converted into a success by Brown Boveri in Switzerland in the early thirties.

George J. Huebner (1963) working at home in Bloomfield Hills, Michigan. (Photo courtesy of George Huebner).

Aurel Stodola, an early gas turbine enthusiast and a pioneer turbine theoretician in what is now the ETH (university) in Zurich, tested a Holzwarth "explosion" (constant-volume-combustion) gas turbine and found very high heat-transfer rates in the water jackets[2]. Gas turbines of those days had to be constructed from what would today be regarded as low-grade stainless steels, and they required a great deal of cooling water. Noack of Brown Boveri thought of using this drawback as a virtue. The water-cooled combustor was greatly enlarged to become a pressurized steam generator. The higher pressure and the high gas velocities resulted in it being much smaller than existing atmospheric-pressure boilers. It was called the "Velox" supercharged boiler and was produced initially in 1932.

Brown Boveri soon changed it to work on today's constant-pressure cycle, and improved the compressor and turbine efficiencies so that by 1935 the shaft, instead of requiring electrical power input, produced a useful power surplus. The first "pure" gas turbine producing shaft power at a useful level was developed by Brown Boveri from its Velox boiler, and commercial sales started in 1939.

Huebner probably saw reports of this engine's development; but it was a large, heavy machine and didn't seem to ordinary mortals to have any promise as an automobile engine.

In 1938 Huebner could not have known about the secret programs that had been underway by Whittle in Britain since around 1930, and by von Ohain in Germany since 1935, to develop the aircraft jet engine. However, Huebner's 1938 report concluded that the automotive gas turbine had potential, but new materials and a great deal of development work would be needed to make it a reality.

Huebner had other things to do for the next few years, but he started an exploratory program in 1944 that so impressed the U.S. Navy that Chrysler was given a contract to design and develop a 1000-hp (746-kW) turboprop (aircraft) engine with a fixed-surface heat exchanger (recuperator). It had a specific fuel consumption of about 0.50 lb/hp-h

(0.3 kg/kWh) at cruise[3], a remarkably low level for that period.

In 1951, Huebner, by this time Chief Engineer, Research for Chrysler, pioneered again by designing an automotive engine that incorporated a moving surface heat exchanger known as a regenerator. (An aircraft engine could operate near its design point for long periods, whereas an automobile engine operates most of its life at below 30% power. A regenerator and a lower engine pressure ratio were therefore needed to give the wide range of high-efficiency operation required). The regenerative engine was demonstrated to the public and the press in 1952. Not only have almost all automotive gas turbines since then incorporated a heat exchanger to recover heat from the hot exhaust and to transfer it to the air leaving the compressor, thus saving much fuel, but recent NASA-sponsored reports are advocating heat exchangers for turboshaft engines in helicopters.

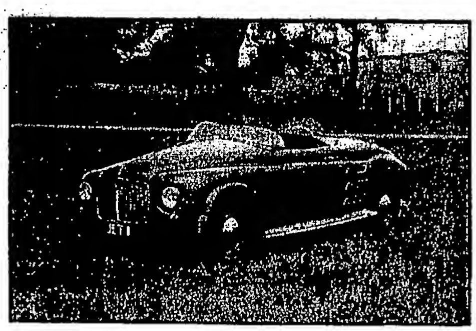
Later Huebner purchased ceramic materials from Corning Glass to experiment with a ceramic-matrix regenerator, and Chrysler and Corning arrived at a cooperative agreement to perform joint research on ceramic regenerators. Despite these efforts, Huebner stayed with stainless-steel matrices for the regenerators on Chrysler's automotive gas turbines ... he felt that ceramics had not proven themselves to be sufficiently reliable at that point.

Rotary regenerators themselves were invented by Fredrik Ljungstrom in 1920 and applied principally to preheating air for steam generators, taking heat from the stack gases[4]. According to another pioneer of the automotive gas turbine, Noel Penny, it was a Dr. Ritz who, after fleeing from Austria prior to World War II, proposed the application of the rotary regenerator to the gas turbine. This started valuable R&D work at the UK National Gas Turbine Establishment[5]. Ritz was inspired by a book on the theory of heat exchangers and regenerators by Hausen (1929). Ritz was joined in Britain by another refugee from Vienna, Waldo Hyriniszak, who became the chief lecturer on heat exchangers for Power Jets, the company and school founded by Frank Whittle.

MAURICE WILKS AND FRANK BELL

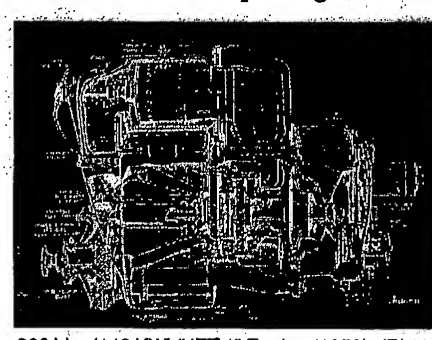
Whittle's part-collaborator, part-rival in Britain, Maurice Wilks, was chief engineer of Rover, one of Britain's foremost manufacturers of high-quality automobiles. Wilks had a burning ambition to replace the piston engine and was determined to show how it could be done[6]. At that time Britain led the world in jet engine and gas turbine design ... Rover had been involved in Whittle's Power Jets W.2 engine[7], and its plant was located close to jet engine manufacturers such as Rolls-Royce, Armstrong-Siddeley, De Havilland and Napier, and close to the Leicester (Whetstone) facility of the National Gas Turbine Establishment.

Wilks was joined by Frank Bell from Rolls-Royce in1945; they designed in that year the first of the company's small turbine engines. It was a two-shaft arrangement, with a centrifugal compressor and axial turbines, and with a pair of plate-fin recuperators. The "gasifier" part of the engine (the compressor and the high-pressure turbine that drove it) was built and tested by 1947. The experience led them to go to an engine of double the power, 200 bhp (149 kW), of rather similar configuration. A succession of variations followed in the normal pattern of development of any new device. The fifth engine of this series was fitted, without a recuperator, into a production Rover sedan re-engineered as a convertible. Its fuel consumption was 0.3 gallons per mile (5.4 km/liter). The car was dubbed the "JET 1."



The Rover JET 1 (1950), the world's first gas turbine-powered automobile. (Photo courtesy of Noël Penny Associates).

When, in 1950, the BBC reported that the world's first gas turbine engined car had been produced at Rover, we ordinary members of the British public swelled with pride and felt that it was only natural that the British should be first in this as in other related fields. I had grown up as a boy in the war accustomed to having a steady diet of such reports, presumably put out by the Ministry of Information as an antidote to the setbacks occurring in most other areas. We were in little better shape in 1950 than we were in the war ... Britain was close to national bankruptcy. The report of Rover's turbine car was therefore uplifting.



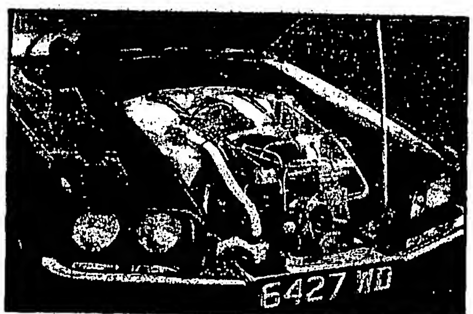
200 bhp (149 KW) "JET 1" Engine (1950). (Photo courtesy of Noël Penny Associates).

I can only speculate on the effect of the news on George Huebner. He may have been chagrined at the thought of being beaten by a team that had come to the field much later than he. On the other hand, both he and Chrysler may have been encouraged to make even greater investments in this developing technology. In any case, Heubner recognized that the Rover "JET 1," while being a remarkable and praiseworthy devel-

opment, was more of a test bed than a serious contender at housing an alternative power plant. Development was only just beginning.

NOËL PENNY

Noël Penny had meanwhile begun to work for Rover in 1950 on loan from a government laboratory, purely to apply his heat transfer and fluid mechanic skills to heat exchanger and engine design. However, he was soon given responsibility for the whole engine. Penny and his team scaled back the size of the engine of "JET 1" to give a maximum power output of 100 bhp (75 kW), a closer fit to then-prevailing British cars, although after development it produced 120 bhp (89.5 kW). There followed a series of engines and cars that established speed records and increased the public's confidence in the future of turbine automobiles.



Rover T4 pre-production sedan (1959). (Photo courtesy of Noël Penny Associates).

A great deal of effort went into the development of satisfactory heat exchangers, almost all of the fixed surface (recuperative) type, and almost all having an effectiveness of about 75%. One of these, fitted to an engine designated 2S/100, was used in a car that covered many thousands of miles in tests on British roads, and gave 11.7 mpg (5 km/l) at 60 mph (96 km/h).

AN AUDACIOUS DEMONSTRATION BY CHRYSLER

Meanwhile, in the mid-1950s, Huebner's team began producing a series of cars with turbine engines aimed squarely at replacing, eventually, the spark-ignition engine. A Plymouth Sport Coupe was produced in 1954 and a revised version a year later. In 1956 a Plymouth four-door sedan with a second-generation engine was driven from New York City to Los Angeles, 3020 miles (4860 km), at an average of 13 mpg (5.5 km/l), close to the average of all gasoline engined cars of that time. This was one result of testing hundreds of similar configurations of regenerators with different materials.

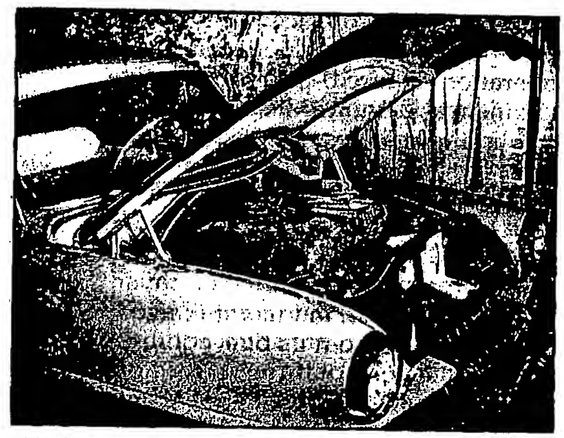
In 1958 a new turbine with variable nozzle settings on the power turbine was installed in a Plymouth four-door hardtop and ran 576 miles (927 km) at 19.4 mpg (8.25 km/l). A third-generation turbine in 1960 had a turbine inlet temperature of 1700°F (927°C), a pressure ratio of 4:1, and a regenerator effectiveness of 0.9. Three vehicles with this turbine were exhibited at the ASME TurboExpo in March 1961.

In 1963 Huebner and Chrysler carried out the most audacious demonstration of a new technology in the history of automobiles.

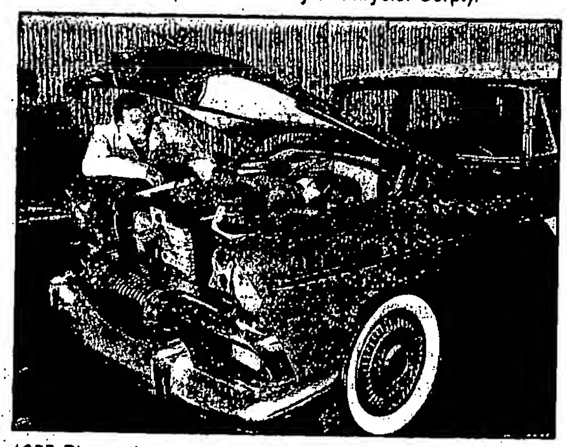
A fourth-generation turbine had been developed, with two side-mounted copper brazed stainless steel regenerators and a maximum output of 130 hp (97 kW). This was fitted to a fleet of 50 extremely handsome cars. The Chrysler designed body was hand-built by Ghia in Turin, Italy. Unfortunately, the prototype went down with the ill-fated ship, the Andrea Doria. When the cars were finally assembled, they were loaned to 203 selected members of the public (23 women, 180 men) in 133 cities for up to three months. The fleet amassed over a million miles without major engine breakdowns.

This stunning success seemed to indicate that the age of turbine automobiles was just around the corner.

Huebner was made Director of Research at Chrysler in 1964, and planned to put his fifth generation turbine in 200 cars. These engines were designed to reduce acceleration lag (partly by driving the accessories off the power-turbine shaft) from 2 to 1.2 seconds. This lag had been the only topic of mild complaint from users of the demonstration vehicles. The turbine inlet temperature was increased to peak at 2000°F (1010°C). However, the provisions of the 1966 Clean Air Act killed the project, even though the turbine was potentially much cleaner than the SI engine.

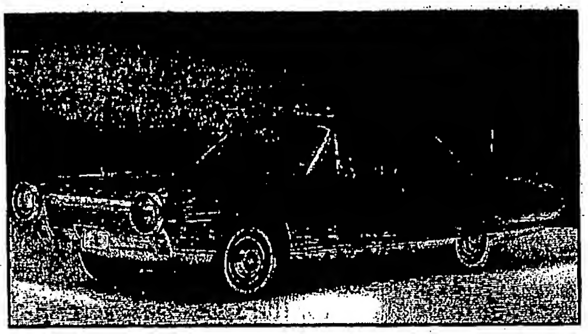


1954 Plymouth Sport Coupe, Chrysler's first gas turbine powered automobile. (Photo courtesy of Chrysler Corp.).

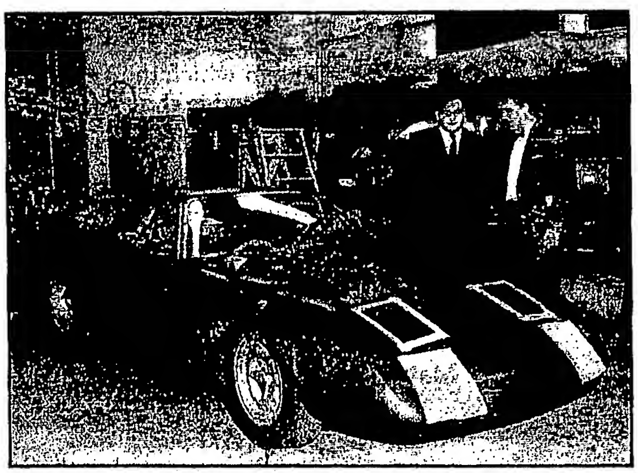


1955 Plymouth experimental gas turbine automobile. (Photo courtesy of Chrysler Corp.).

There was another drawback that has dogged the turbine, revealed by Huebner to MIT students at a campus seminar about 1967: whereas the manufacturing cost in full production of the standard gasoline engine was only about $1.50 per hp, including the cost of materials (mostly cast iron and steel), gas turbine materials alone (having high nickel, chromium and cobalt content) cost over $8 per hp. Huebner thought that he was close to a solution, but that was not to be. We would have to wait for major developments in ceramics, and perhaps in composites, before we could contemplate acceptable production costs for gas turbine engines.



1963 Chrysler Turbine, designed by Chrysler stylists and engineers and hand-built by Ghia. (Photo courtesy of Chrysler Corp.).



Noël Penny (left) showing the 1964 Rover BRM to Peter Candy. (Photo courtesy of Noël Penny Associates).

THE ROVER RACE

Also in the ealy 1960s, Rover and Noël Penny made their own audacious demonstration of gas turbine powered cars, by entering them in the most prestigious event in European sports car racing, the Le Mans 24-hour race. A recuperated version of the Rover was introduced at the New York Automobile Show in April 1962 and gave a demonstration run before (but not in) the Le Mans race in June.

An improved version, but with no heat exchanger, was entered in the 1963 Le Mans race; but because no category for turbine cars existed, it was effectively in a race of one. The car ran reliably throughout the race (typically over half the cars drop out), finishing with an average speed of 107 mph and an average consumption of 6 mpg (US).

The stainless steel recuperators that had been under development had short lives, but Noël Penny was encouraged by the progress in projects at Corning (initiated by Huebner) to design a glass-ceramic regenerator. In 1965, Penny entered a regenerative Rover-BRM car in the Le Mans race. That entry was to have a dramatic affect upon the course of automotive gas turbine history.

leaky recuperator

Early in the race the car came into the pits because of reduced power and high turbine inlet temperature. There seemed nothing that could be done, and the car was sent back into the race. It finished in tenth place at an average speed of about 98 mph and a fuel consumption of just under 11.5 mpg. This was a high achievement in itself, considering that, as in every race, most cars fail at some point. What was even more remarkable was that when the engine was opened it was found to have suffered serious compressor-blade failure as the result of some inappropriate machining to balance the rotor. Parts of compressor blades had embedded themselves in the regenerator disk, passing under the seals at every revolution.

I remember the excitement as this news spread throughout the gas turbine community. A wave of enthusiasm for the Corning regenerator material swept the industry. I believe this enthusiasm influenced Ford in its decision to develop a regenerated truck engine. This next phase of the story will appear in the August/September issue of your *Global Gas Turbine News*. ❋ End

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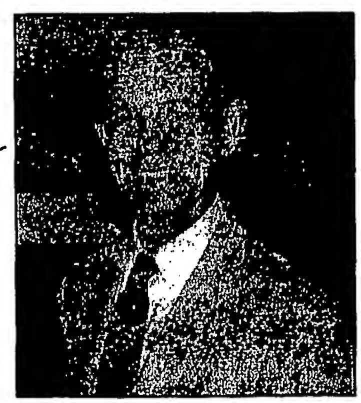

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